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Simulation and analysis of wastewater stabilization pond system

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Abstract— In this study, an ecological model established by the authors is used to simulate the general operation characteristics of wastewater stabilization pond system. Some conclusions are useful for understanding the mechanisms of stabilization pond, and the design and operation of the pond system.

Keywords: ecological model; simulation; wastewater stabilization pond.

1 Model introduction

Wastewater stabilization pond is a complicated semi-artificial ecosystem, in which various biota and biochemical processes proceeded. For systematically recognizing the behavior of the pond system in general operation conditions, the simulation and analysis on pond system have been conducted using the ecological model established by the authors (Wen, 1991).

An ecological model which describes the transformation of carbon, nitrogen and phosphorus in wastewater stabilization pond system based on lab-scale experiments have been established (Wen, 1991). All parameters in the model were determinated through the model calibration on the data obtained from experiments. The size of the lab-scale pond and the operation conditions of that pond are shown in Table 1 and Table 2. Model verification using full-scale pond information was also conducted. The study has demonstrated that the model structure is proper, the parameter values are satisified in application and the model solution technique is successful. The model is listed in Eq. 1–Eq.12. It consists of twelve non-linear equations which mainly include two types of sub-model: the Monod equation for the growth of microbes and the first-order expression for all the other biochemical reactions such as biodecay, biolysis and organism settling, and so on. The subscript "i" refers to the influent. The variables in the model are listed in Table 3.

Table 1 Size of the lab pond

Pond No.	1	2	3
Length, m	0.785	0.785	0.785
Width, m	0.400	0.225	0.225
Depth, m	0.495	0.495	0.495
Areas, m^2	0.314	0.177	0.177
Vol., m^3	0.155	0.087	0.087

Table 2 Operation conditions of the experiments

No.	Temp., ℃	F.R., L/d	HRT, d	COD, mg/L	TC, mg/L	TN, mg/L	TP, mg/L
1	20	38.3	8.6	109.72	83.89	14.55	1.63
2	20	34.8	9.4	187.21	110.84	21.01	2.21
3	20	30.0	11.0	246.95	126.58	26.56	2.65
4	20	30.0	11.0	302.81	147.04	33.07	3.36

Note: F.R: Flow rate

Table 3 Variables in model

Unit: mg/L

Name	Symbol
Inorganic carbon	C_I
Carbon content in bacterial cells	C_B
Organic carbon	C_O
Carbon content in algal cells	C_A
Inorganic nitrogen	N_I
Nitrogen content in bacterial cells	N_B
Organic nitrogen	N_O
Nitrogen content in algal cells	N_A
Total phosphorus	P_T
Phosphorus content in bacterial cells	P_B
Phosphorus content in algal cells	P_A

Carbon:

$$\frac{G_{Ii}}{\theta} - \frac{C_I}{\theta} + (1-Y)\mu_{mBC}\frac{C_0}{K_{BC}+C_0} \cdot C_B/Y + k_{dBC} \cdot C_B$$

$$+ k_{dAC} \cdot C_A - \mu_{mAC}\frac{C_I}{K_{AC}+C_I} \cdot C_A \cdot f(I) = 0, \tag{1}$$

$$\frac{C_{Bi}}{\theta} - \frac{C_B}{\theta} + \mu_{mBC}\frac{C_0}{K_{BC}+C_0} \cdot C_B - k_{dBC} \cdot C_B = 0, \tag{2}$$

$$\frac{C_{Oi}}{\theta} - \frac{C_O}{\theta} - \mu_{mBC}\frac{C_0}{K_{BC}+C_0} \cdot C_B/Y + k_{LC} \cdot C_A = 0, \tag{3}$$

$$\frac{C_{Ai}}{\theta} - \frac{C_A}{\theta} + \mu_{mAC}\frac{C_I}{K_{AC}+C_I} \cdot C_A \cdot f(I)$$

$$- k_{dAC} \cdot C_A - k_{LC} \cdot C_A - k_{SC} \cdot C_A = 0. \tag{4}$$

Nitrogen:

$$\frac{N_{Ii}}{\theta} - \frac{N_I}{\theta} + \alpha_N \cdot N_O + k_{dBN} \cdot N_B + k_{dAN} \cdot N_A$$

$$- \mu_{mBN}\frac{N_I}{K_{BN}+N_I} \cdot N_B - \mu_{mAN}\frac{N_I}{K_{AN}+N_I} \cdot N_A \cdot f(I) = 0, \tag{5}$$

$$\frac{N_{Bi}}{\theta} - \frac{N_B}{\theta} + \mu_{mBN}\frac{N_I}{K_{BN}+N_I} \cdot N_B - k_{dBN} \cdot N_B = 0, \tag{6}$$

$$\frac{N_{Oi}}{\theta} - \frac{N_O}{\theta} - \alpha_N \cdot N_O + k_{LN} \cdot N_A = 0, \tag{7}$$

$$\frac{N_{Ai}}{\theta} - \frac{N_A}{\theta} + \mu_{mAN} + \frac{N_I}{K_{AN}+N_I} \cdot N_A \cdot f(I) - k_{dAN} \cdot N_A$$

$$- k_{LN} \cdot N_A - k_{SN} \cdot N_A = 0. \tag{8}$$

Phosphorus:

$$\frac{P_{Ti}}{\theta}-\frac{P_T}{\theta}+k_{dBP}\cdot P_B+k_{dAP}\cdot P_A-\mu_{mBP}\frac{P_T}{K_{BP}+P_T}\cdot P_B$$

$$-\mu_{mAP}\frac{P_T}{K_{AP}+P_T}\cdot P_A\cdot f(I)+k_{LP}\cdot P_A=0, \tag{9}$$

$$\frac{P_{Bi}}{\theta}-\frac{P_B}{\theta}+\mu_{mBP}\frac{P_T}{K_{BP}+P_T}\cdot P_B-k_{dBP}\cdot P_B=0, \tag{10}$$

$$\frac{P_{Ai}}{\theta}-\frac{P_A}{\theta}+\mu_{mAP}\frac{P_T}{K_{AP}+P_T}\cdot P_A\cdot f(I)-k_{dap}\cdot P_A$$

$$-k_{LP}\cdot P_A-k_{SP}\cdot P_A=0. \tag{11}$$

Function of light:

$$f(I)=\frac{I_{av}}{I_m}exp(1-\frac{I_{av}}{I_m}). \tag{12}$$

2 Simulation conditions

Five states of simulation conditions are listed in Table 4. It is for a 3 stage pond system with the detention time of 5 d for the first pond and 2.5 d for the second and third pond.

Table 4 Simulation conditions

Unit: mg/L

State	1	2	3	4	5
C_{Oi}	24.00	48.00	72.00	96.00	120.00
TN_i	14.20	19.00	23.80	28.60	33.40
N_{Ii}	2.13	2.85	3.57	4.29	5.01
N_{Oi}	12.00	16.15	20.23	24.31	28.39
P_{Ti}	1.47	1.97	2.46	2.96	3.46

3 Results and analysis

3.1 The effects of influent concentration

The variations of each variable with the change of influent concentration are clearly presented in Fig.1 – Fig.9 which are of significance for further understanding the pond mechanism of stabilization pond.

3.1.1 Carbon

The simulation results of carbon are shown in Fig.1 – Fig.3.

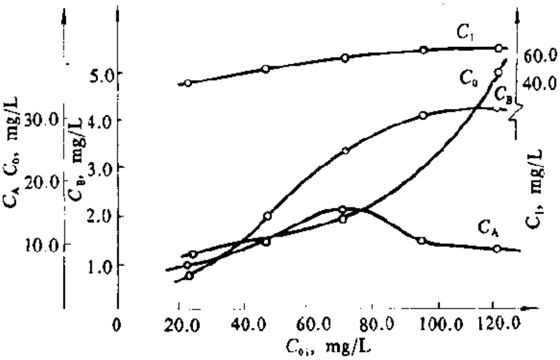

Fig. 1 Carbon simulation result in pond 1

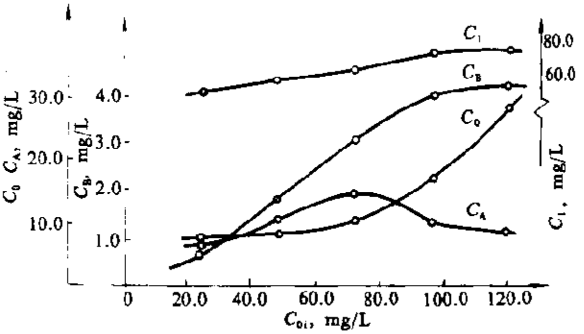

Fig.2 Carbon simulation result in poond 2

In all three stages of the pond system, the concentrations of inorganic carbon only have a slight increase with the increase of influent concentration of organic carbon. It demonstrates that the inorganic carbon is rather steady and the responds of inorganic carbon in each stage of the pond system to the influent organic carbon are the same. The reason for the increase of inorganic carbon is that the rate of algal photosynthesis is not higher than that of the bacteria metabolism. It is suggested that the growth of algae may be limited by its own growth rate or other environment factors such as light rather than the inorganic carbon source.

With the increase of influent organic carbon, the carbon content in bacterial cells increase obviously at the begining and then the increase rate was lower down, which suited Monod equation well and was similar to all three stages of the pond.

The organic carbon in all three stages of the pond system have the same response to influent organic carbon. The organic carbon in pond increase with the increase of influent organic carbon. It is proven that although the operation stability of multi-stage pond would be higher, its ability for stabilizing organic carbon has a limitation. For assuring an acceptable effluent quality, the influent concentration or the organic loading of a stabilization pond should be controlled carefully.

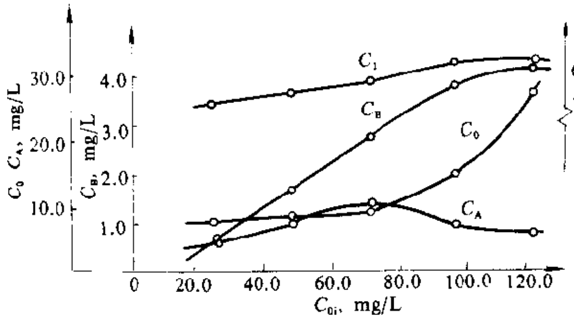

Fig. 3 Carbon simulation result in pond 3

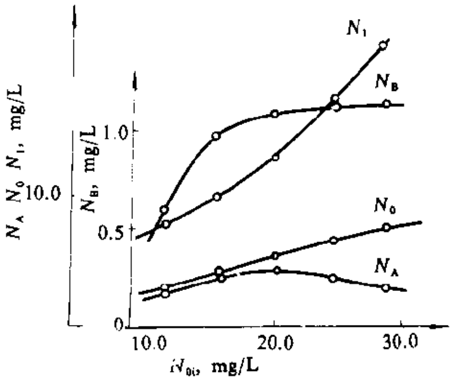

Fig. 4 Nitrogen simulation result in pond 1

The carbon content in algal cells reachs its top value in state 3 for pond system, which indicates that the nutrient level in state 3 is the optimum one for algae growth. Much higher influent concentration leads to vigorous growth of bacteria, while much lower influent concentration would result in nutrient deficiency. Both would limit the algae growth.

3.1.2 Nitrogen

Fig. 4—Fig.6 are the simulation results for nitrogen.

Inorganic nitrogen concentration increases with the increase of influent organic nitrogen in all three stages of the pond system, which indicates that the inorganic nitrogen produced from ammoniation of organic nitrogen is more than what needed for algal growth.

The change of nitrogen content in bacterial cells exactly follows the Monod Equation for each stage of the pond.

Organic nitrogen increases with the increase of influent organic nitrogen and the concentration of it is much lower than that of inorganic nitrogen. It shows that the ammoniation proceeds perfectly and produces a large quantity of inorganic nitrogen which can not be absorbed by algae in time. It indicates that the assimilation ability of algae to nitrogen has a limit. It is also proven that the nitrification and denitrification process does not proceed well in the pond system because of the environmental condition and the inhibition of high concentration of ammonia.

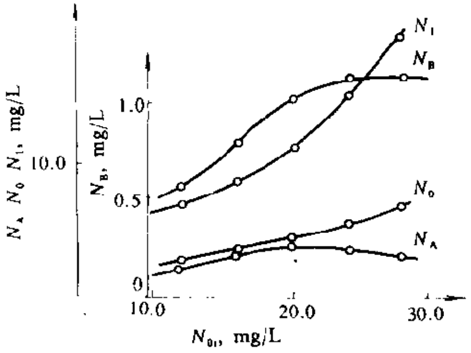

Fig. 5 Nitrogen simulation result in pond 2

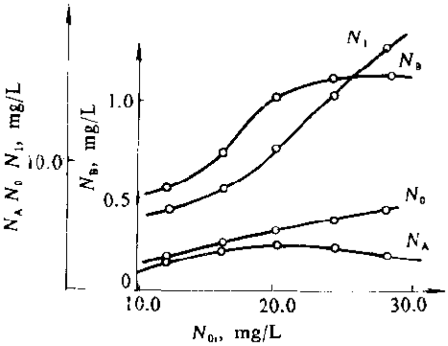

Fig. 6 Nitrogen simulation result in pond 3

The change of nitrogen content in algal cells is the same to that of the carbon content in algal cells.

3.1.3 Phosphorus

Phosphorus simulation results are presented in Fig. 7—Fig.9.

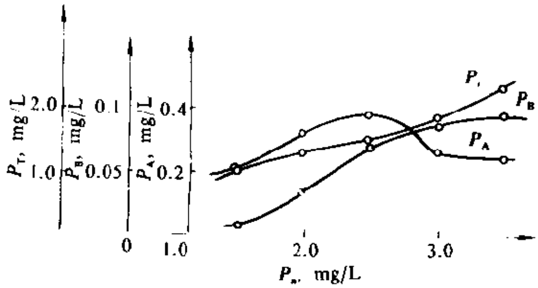

Fig. 7 Phosphorus simulation result in pond 1

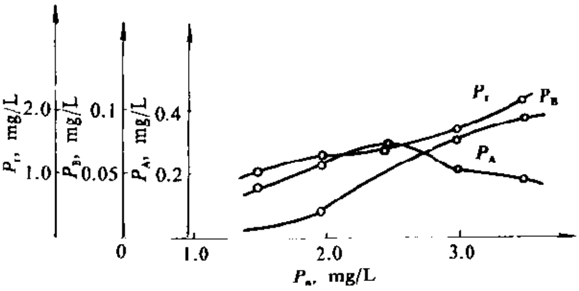

Fig. 8 Phosphorus simulation result in pond 2

Phosphorus concentrations in all three stages of the pond system increase with the increase of influent phosphorus concentration. Just like the above analysis on carbon, it is not proper to run a stabilization pond system at too high influent concentration of phosphorus because it will certainly affect the effluent quality.

It can be seen that the variations of phosphorus content in bacterial and algal cells are quite similar to that of the carbon content in bacterial and algal cells.

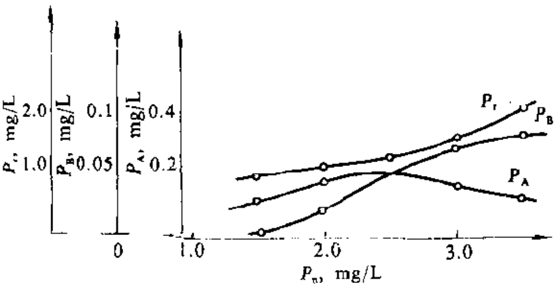

Fig. 9 Phosphorus simulation result in pond 3

3.2 The effect of hydraulic retention time

The time dependent variations of variables in stage 1,3 and 5 (Table 2) are presented in Fig. 10—Fig. 15 where the number in parenthesis represents simulation state.

3.2.1 Carbon

Time-dependent changes of different forms of carbon are shown in Fig. 10 and Fig.11.

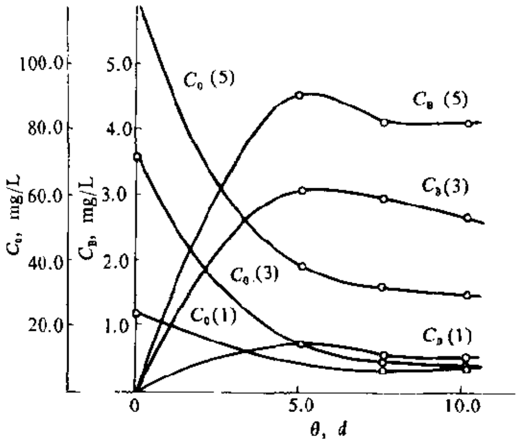

Fig. 10 Time dependent variations of C_B, Co

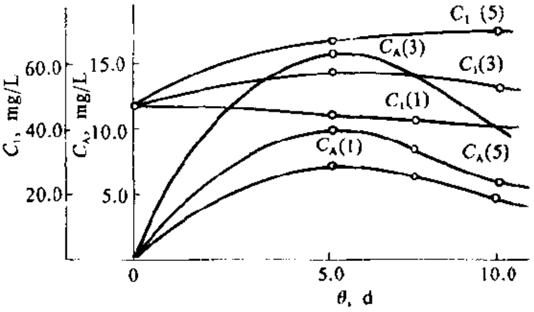

Fig. 11 Time dependent variations of C_I, C_A

Fig. 10 shows that the organic carbon decreases sharply in pond 1 and then decreases slowly. The slope of the curve for high influent concentration is larger than that for lower influent concentration. These phenomena comply with the general rule.

The carbon contents in bacterial and algal cells reach their top value in pond 1 and then decrease.

The variation of inorganic carbon is shown in Fig. 11. For higher influent concentration, the inorganic carbon increases slightly with time which indicates that the carbon dioxide created by bacteria action on organic carbon surpasses that required by algae, however, for the influent concentration is lower, the inorganic carbon decreases with time. It shows that under these conditions, the carbon dioxide released from organic carbon decomposition by bacteria is not enough for algae demanding. The carbonic acid system provide some carbon dioxide for algae as compensation.

3.2.2 Nitrogen

Fig. 12 and Fig. 13 are the time dependent variations of nitrogen.

Organic nitrogen decreases quickly in pond 1 and the decrease rate is much lower in pond 2. While in pond 3 organic nitrogen concentration increases slightly because of the bio-lysis.

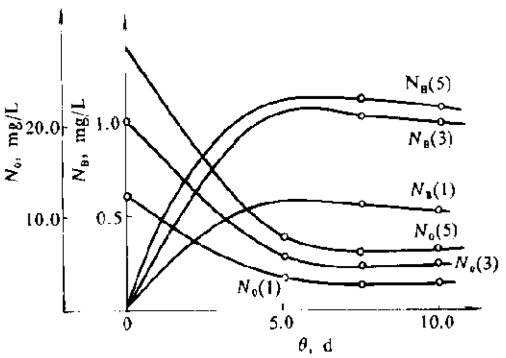

Fig. 12 Time dependent variations of N_O, N_B

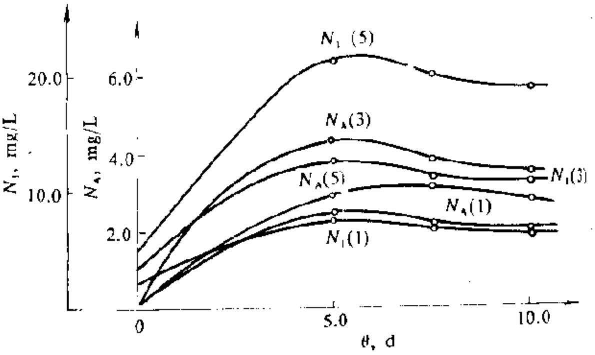

Fig. 13 Time dependent variations of N_I, N_A

The changes of nitrogen contents in bacterial and algal cells are similar to that of carbon contents in bacterial and algal cells.

The inorganic nitrogen concentration reaches its top value in pond 1 due to high ammoniation rate and then decreases.

3.2.3 Phosphorus

Phosphorus variations are shown in Fig. 14 and Fig. 15.

Phosphorus decreases with the time smoothly.

The variations of phosphorus contents in bacterial and algal cells are quite similar to that of the carbon contents in bacterial and algal cells.

4 Conclusions

Based on the results of the simulation and analysis, the general operation

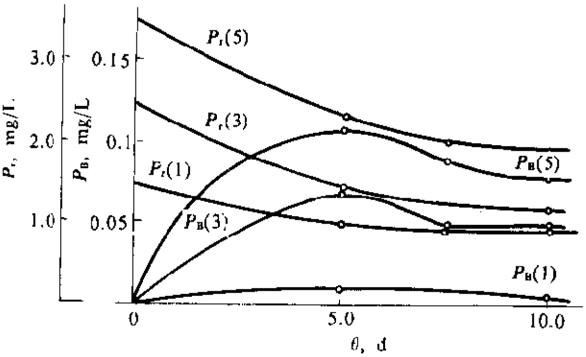

Fig. 14 Time dependent variations of P_T, P_B

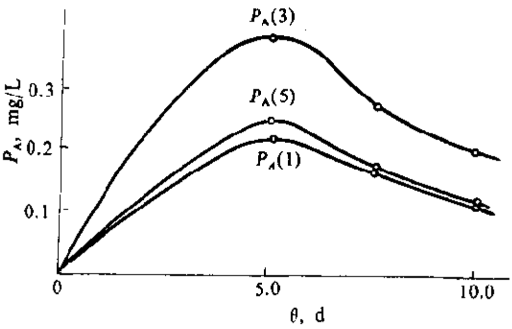

Fig. 15 Time dependent variations of P_A

characteristics of pond system are as follows:

Organic carbon concentration in each stage of a multi-stage pond increases with the increases of influent concentration. It is not proper to run a multi-stage pond at too high influent carbon concentration and this is also truth for nitrogen and phosphorus.

The removal rate of organic nitrogen is as higher as about 90% in stabilization pond system, but it is only about 50% for total nitrogen, the pond system has a limited ability for removing inorganic nitrogen.

The respondences of carbon, nitrogen and phosphorus contents in bacterial cells to the influent concentrations are all follow Monod equation.

The respondences of carbon, nitrogen and phosphorus content in algal cells are similar. There exists an optimum nutrient concentration for algal e growth. The elevation of algal concentration is beneficial to the removal of dissolved nutrients.

The time dependent variations of carbon, nitrogen and phosphorus contents in bacterial and algal cells are the same. They all have their top value in pond 1 and then decrease.

Dissolved organic carbon and nitrogen decrease sharply in pond 1.

The variations of inorganic carbon concentration depend on influent concentration. Phosphorus decreases with time.

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